## 8.1 Drought

The word "drought" brings to mind abnormally dry conditions. However, the meaning of "dry" can be ambiguous and lead to confusion in how drought is actually defined. Three different classes of droughts are defined by NOAA and describe a useful hierarchal set of water deficit characterization, each with different impacts. "Meteorological drought" describes conditions of precipitation deficit. "Agricultural drought" describes conditions of soil moisture deficit. "Hydrological drought" describes conditions of deficit in runoff.[1] Clearly these three characterizations of drought are related but are also different descriptions of water shortages with different target audiences and different time scales. In particular, agricultural drought is of concern to producers of food while hydrological drought is of concern to water system managers. Soil moisture is a function of both precipitation and evapotranspiration. Because potential evapotranspiration increases with temperature, anthropogenic climate change generally results in drier soils and often less runoff in the long term. In fact, under the higher scenario (RCP8.5; see Ch. 4: Projections for a description of the RCP scenarios) at the end of the 21st century, no region of the planet is projected to experience significantly higher levels of annual average surface soil moisture due to the sensitivity of evapotranspiration to temperature, even though much higher precipitation is projected in some regions.[2] Seasonal and annual total runoff, on the other hand, are projected to either increase or decrease, depending on location and season under the same conditions,[2] illustrating the complex relationships between the various components of the hydrological system. Meteorological drought can occur on a range of time scales, in addition to seasonal or annual time scales. "Flash droughts" can result from just a few weeks of dry weather,[3] and the paleoclimate record contains droughts of several

decades. Hence, it is vital to describe precisely the definition of drought in any public discussion to avoid confusion due to this complexity. As the climate changes, conditions currently considered "abnormally" dry may become relatively "normal" in those regions undergoing aridification, or extremely unlikely in those regions becoming wetter. Hence, the reference conditions defining drought may need to be modified from those currently in practice.

### 8.1.1 Historical Context

The United States has experienced all three types of droughts in the past, always driven, at least in some part, by natural variations in seasonal and/or annual precipitation amounts. As the climate changes, we can expect that human activities will alter the effect of these natural variations. The "Dust Bowl" drought of the 1930s is still the most significant meteorological and agricultural drought experienced in the United States in terms of its geographic and temporal extent. However, even though it happened prior to most of the current global warming, human activities exacerbated the dryness of the soil by the farming practices of the time.[4] Tree ring archives reveal that such droughts (in the agricultural sense) have occurred occasionally over the last 1,000 years.[5] Climate model simulations suggest that droughts lasting several years to decades occur naturally in the southwestern United States.[6] The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5)[7] concluded "there is low confidence in detection and attribution of changes in (meteorological) drought over global land areas since the mid-20th century, owing to observational uncertainties and difficulties in distinguishing decadal-scale variability in drought from long-term trends." As they noted, this was a weaker attribution statement than in the Fourth Assessment Report,[8] which had concluded "that an increased risk of drought was *more likely than not* due to

anthropogenic forcing during the second half of the 20th century." The weaker statement in AR5 reflected additional studies with conflicting conclusions on global drought trends (e.g., Sheffield et al. 2012;[9] Dai 2013[10]). Western North America was noted as a region where determining if observed recent droughts were unusual compared to natural variability was particularly difficult. This was due to evidence from paleoclimate proxies of cases of central U.S. droughts during the past 1,000 years that were longer and more intense than historical U.S. droughts.[11] Drought is, of course, directly connected to seasonal precipitation totals. Figure 7.1 shows detectable observed recent changes in seasonal precipitation. In fact, the increases in observed summer and fall precipitation are at odds with the projections in Figure 7.5. As a consequence of this increased precipitation, drought statistics over the entire CONUS have declined.[3, 12] Furthermore, there is no detectable change in meteorological drought at the global scale.[9] However, a number of individual event attribution studies suggest that if a drought occurs, anthropogenic temperature increases can exacerbate soil moisture deficits (e.g., Seager et al. 2015;[13] Trenberth et al. 2014[14]). Future projections of the anthropogenic contribution to changes in drought risk and severity must be considered in the context of the significant role of natural variability.

### 8.1.2 Recent Major U.S. Droughts

*Meteorological and Agricultural Drought*
The United States has suffered a number of very significant droughts of all types since 2011. Each of these droughts was a result of different persistent, large-scale meteorological patterns of mostly natural origins, with varying degrees of attributable human influence. Table 8.1 summarizes available attribution statements for recent extreme U.S. droughts. Statements about meteorological drought are decidedly mixed, revealing the complexities

in interpreting the low tail of the distribution of precipitation. Statements about agricultural drought consistently maintain a human influence if only surface soil moisture measures are considered. The single agricultural drought attribution study at root depth comes to the opposite conclusion.[15] In all cases, these attribution statements are examples of attribution without detection (see Appendix C). The absence of moisture during the 2011 Texas/Oklahoma drought and heat wave was found to be an event whose likelihood was enhanced by the La Niña state of the ocean, but the human interference in the climate system still doubled the chances of reaching such high temperatures.[16] This study illustrates that the effect of human-induced climate change is combined with natural variations and can compound or inhibit the realized severity of any given extreme weather event.

The Great Plains/Midwest drought of 2012 was the most severe summer meteorological drought in the observational record for that region.[17] An unfortunate string of three different patterns of large-scale meteorology from May through August 2012 precluded the normal frequency of summer thunderstorms and was not predicted by the NOAA seasonal forecasts.[17] Little influence of the global sea surface temperature (SST) pattern on meteorological drought frequency has been found in model simulations.[17] No evidence of a human contribution to the 2012 precipitation deficit in the Great Plains and Midwest is found in numerous studies.[17, 18, 19] However, an alternative view is that the 2012 central U.S. drought can be classified as a "heat wave flash drought",[20] a type of rapidly evolving drought that has decreased in frequency over the past century.[3] Also, an increase in the chances of the unusually high temperatures seen in the United States in 2012, partly associated with resultant dry summer soil moisture anomalies, was attributed to the human interference with the

climate system,[21] indicating the strong feed-back between lower soil moisture and higher surface air temperatures during periods of low precipitation. One study found that most, but not all, of the 2012 surface moisture deficit in the Great Plains was attributable to the precipitation deficit.[22] That study also noted that Great Plains root depth and deeper soil mois-

**Table 8.1.** A list of U.S. droughts for which attribution statements have been made. In the last column, "+" indicates that an attributable human-induced increase in frequency and/or magnitude was found, "–" indicates that an attributable human-induced decrease in frequency and/or magnitude was found, "0" indicates no attributable human contribution was identified. As in Tables 6.2 and 7.1, several of the events were originally examined in the Bulletin of the American Meteorological Society's (BAMS) State of the Climate Reports and reexamined by Angélil et al.[18] In these cases, both attribution statements are listed with the original authors first. (Source: M. Wehner)

| Authors | Event Year and Duration | Region or State | Type | Attribution Statement |
|---|---|---|---|---|
| Rupp et al. 2012[130] / Angélil et al. 2017[18] | MAMJJA 2011 | Texas | Meteorological | +/+ |
| Hoerling et al. 2013[16] | 2012 | Texas | Meteorological | + |
| Rupp et al. 2013[19] / Angélil et al. 2017[18] | MAMJJA 2012 | CO, NE, KS, OK, IA, MO, AR & IL | Meteorological | 0/0 |
| Rupp et al. 2013[19] / Angélil et al. 2017[18] | MAM 2012 | CO, NE, KS, OK, IA, MO, AR & IL | Meteorological | 0/0 |
| Rupp et al. 2013[19] / Angélil et al. 2017[18] | JJA 2012 | CO, NE, KS, OK, IA, MO, AR & IL | Meteorological | 0/+ |
| Hoerling et al. 2014[17] | MJJA 2012 | Great Plains/Midwest | Meteorological | 0 |
| Swain et al. 2014[24] / Angélil et al. 2017[18] | ANN 2013 | California | Meteorological | +/+ |
| Wang and Schubert 2014[29] / Angélil et al. 2017[18] | JS 2013 | California | Meteorological | 0/+ |
| Knutson et al. 2014[131] / Angélil et al. 2017[18] | ANN 2013 | California | Meteorological | 0/+ |
| Knutson et al. 2014[131] / Angélil et al. 2017[18] | MAM 2013 | U.S. Southern Plains region | Meteorological | 0/+ |
| Diffenbaugh et al. 2015[28] | 2012–2014 | California | Agricultural | + |
| Seager et al. 2015[13] | 2012–2014 | California | Agricultural | + |
| Cheng et al. 2016[15] | 2011–2015 | California | Agricultural | – |
| Mote et al. 2016[31] | 2015 | Washington, Oregon, California | Hydrological (snow water equivalent) | + |

ture was higher than normal in 2012 despite the surface drying, due to wet conditions in prior years, indicating the long time scales relevant below the surface.[22]

The recent California drought, which began in 2011, is unusual in different respects. In this case, the precipitation deficit from 2011 to 2014 was a result of the "ridiculously resilient ridge" of high pressure. This very stable high pressure system steered storms towards the north, away from the highly engineered California water resource system.[13, 23, 24] A slow-moving high sea surface temperature (SST) anomaly, referred to as "The Blob"—was caused by a persistent ridge that weakened the normal cooling mechanisms for that region of the upper ocean.[25] Atmospheric modeling studies showed that the ridge that caused The Blob was favored by a pattern of persistent tropical SST anomalies that were warm in the western equatorial Pacific and simultaneously cool in the far eastern equatorial Pacific.[23, 26] It was also favored by reduced arctic sea ice and from feedbacks with The Blob's SST anomalies.[27] These studies also suggest that internal variability likely played a prominent role in the persistence of the 2013–2014 ridge off the west coast of North America. Observational records are not long enough and the anomaly was unusual enough that similarly long-lived patterns have not been often seen before. Hence, attribution statements, such as that about an increasing anthropogenic influence on the frequency of geopotential height anomalies similar to 2012–2014 (e.g., Swain et al. 2014[24]), are without associated detection (Ch. 3: Detection and Attribution). A secondary attribution question concerns the anthropogenic precipitation response in the presence of this SST anomaly. In attribution studies with a prescribed 2013 SST anomaly, a consistent increase in the human influence on the chances of very dry California conditions was found.[18]

Anthropogenic climate change did increase the risk of the high temperatures in California in the winters of 2013–2014 and 2014–2015, especially the latter,[13, 28, 29] further exacerbating the soil moisture deficit and the associated stress on irrigation systems. This raises the question, as yet unanswered, of whether droughts in the western United States are shifting from precipitation control[30] to temperature control. There is some evidence to support a relationship between mild winter and/or warm spring temperatures and drought occurrence,[31] but long-term warming trends in the tropical and North Pacific do not appear to have led to trends toward less precipitation over California.[32] An anthropogenic contribution to commonly used measures of agricultural drought, including the Palmer Drought Severity Index (PDSI), was found in California[28, 33] and is consistent with previous projections of changes in PDSI[10, 34, 35] and with an attribution study.[36] Due to its simplicity, the PDSI has been criticized as being overly sensitive to higher temperatures and thus may exaggerate the human contribution to soil dryness.[37] In fact, this study also finds that formulations of potential evaporation used in more complicated hydrologic models are similarly biased, undermining confidence in the magnitude but not the sign of projected surface soil moisture changes in a warmer climate. Seager et al.[13] analyzed climate model output directly, finding that precipitation minus evaporation in the southwestern United States is projected to experience significant decreases in surface water availability, leading to surface runoff decreases in California, Nevada, Texas, and the Colorado River headwaters even in the near term. However, the criticisms of PDSI also apply to most of the CMIP5 land surface model evapotranspiration formulations. Analysis of soil moisture in the CMIP5 models at deeper levels is complicated by the wide variety in sophistication of their component land models. A pair of studies reveals less

sensitivity at depth-to-surface air temperature increases than at near-surface levels.[15, 38] Berg et al.[39] adjust for the differences in land component model vertical treatments, finding projected change in vertically integrated soil moisture down to 3 meters depth is mixed, with projected decreases in the Southwest and in the south-central United States, but increases over the northern plains. Nonetheless, the warming trend has led to declines in a number of indicators, including Sierra snow water equivalent, that are relevant to hydrological drought.[30] Attribution of the California drought and heat wave remains an interesting and controversial research topic.

In summary, there has not yet been a formal identification of a human influence on past changes in United States meteorological drought through the analysis of precipitation trends. Some, but not all, U.S. meteorological drought event attribution studies, largely in the "without detection" class, exhibit a human influence. Attribution of a human influence on past changes in U.S. agricultural drought are limited both by availability of soil moisture observations and a lack of subsurface modeling studies. While a human influence on surface soil moisture trends has been identified with *medium confidence*, its relevance to agriculture may be exaggerated.

### Runoff And Hydrological Drought

Several studies focused on the Colorado River basin in the United States that used more sophisticated runoff models driven by the CMIP3 models[40, 41, 42, 43, 44] showed that annual runoff reductions in a warmer western Unites States climate occur through a combination of evapotranspiration increases and precipitation decreases, with the overall reduction in river flow exacerbated by human water demands on the basin's supply. Reduced U.S. snowfall accumulations in much warmer

future climates are virtually certain as frozen precipitation is replaced by rain regardless of the projected changes in total precipitation amounts discussed in Chapter 7: Precipitation Change (Figure 7.6). The profound change in the hydrology of snowmelt-driven flows in the western United States is well documented. Earlier spring runoff[45] reduced the fraction of precipitation falling as snow[46] and the snow-pack water content at the end of winter,[47, 48] consistent with warmer temperatures. Formal detection and attribution (Ch. 3: Detection and Attribution) of the observed shift towards earlier snowmelt-driven flows in the western United States reveals that the shift is detectably different from natural variability and attributable to anthropogenic climate change.[49] Similarly, observed declines in the snow water equivalent in the region have been formally attributed to anthropogenic climate change[50] as have temperature, river flow, and snowpack.[41, 51] As a harbinger, the unusually low western U.S. snowpack of 2015 may become the norm.[31]

In the northwestern United States, long-term trends in streamflow have seen declines, with the strongest trends in drought years[52] that are attributed to a decline in winter precipitation.[53] These reductions in precipitation are linked to decreased westerly wind speeds in winter over the region. Furthermore, the trends in westerlies are consistent with CMIP5-projected wind speed changes due to a decreasing meridional temperature and pressure gradients rather than low-frequency climate variability modes. Such precipitation changes have been a primary source of change in hydrological drought in the Northwest over the last 60 years[54] and are in addition to changes in snowpack properties.

We conclude with *high confidence* that these observed changes in temperature controlled

aspects of western U.S. hydrology are *likely* a consequence of human changes to the climate system.

### 8.1.3 Projections of Future Droughts

The future changes in seasonal precipitation shown in Chapter 7: Precipitation Change (Figure 7.6) indicate that the southwestern United States may experience chronic future precipitation deficits, particularly in the spring. In much warmer climates, expansion of the tropics and subtropics, traceable to changes in the Hadley circulation, cause shifts in seasonal precipitation that are particularly evident in such arid and semi-arid regions and increase the risk of meteorological drought. However, uncertainty in the magnitude and timing of future southwestern drying is high. We note that the weighted and downscaled projections of Figure 7.6 exhibit significantly less drying and are assessed to be less significant in comparison to natural variations than the original unweighted CMIP5 projections.[34]

Western U.S. hydrological drought is currently controlled by the frequency and intensity of extreme precipitation events, particularly atmospheric rivers, as these events represent the source of nearly half of the annual water supply and snowpack for the western coastal states.[55, 56] Climate projections indicate greater frequency of atmospheric rivers in the future (e.g., Dettinger 2011;[55] Warner et al. 2015;[57] Gao et al. 2015;[58] see further discussion in Ch. 9: Extreme Storms). Sequences of these extreme storms have played a critical role in ending recent hydrological droughts along the U.S. West Coast.[59] However, as winter temperatures increase, the fraction of precipitation falling as snow will decrease, potentially disrupting western U.S. water management practices.

Significant U.S. seasonal precipitation deficits are not confidently projected outside of the Southwest. However, future higher tempera- tures will *likely* lead to greater frequencies and magnitudes of agricultural droughts through- out the continental United States as the result- ing increases in evapotranspiration outpace projected precipitation increases.[2] Figure 8.1 shows the weighted multimodel projection of the percent change in near-surface soil moisture at the end of the 21st century un- der the higher scenario (RCP8.5), indicating widespread drying over the entire continental United States. Previous National Climate As- sessments[34, 60] have discussed the implication of these future drier conditions in the context of the PDSI, finding that the future normal condition would be considered drought at the present time, and that the incidence of "extreme drought" (PDSI < −4) would be significantly increased. However, as described below, the PDSI may overestimate future soil moisture drying.

This projection is made "without attribution" (Ch. 4: Projections), but confidence that fu- ture soils will generally be drier at the sur- face is *medium*, as the mechanisms leading to increased evapotranspiration in a warmer climate are elementary scientific facts. Howev- er, the land surface component models in the CMIP5 climate models vary greatly in their so- phistication, causing the projected magnitude of both the average soil moisture decrease and the increased risk for agricultural drought to be less certain. The weighted projected season- al decreases in surface soil moisture are gener- ally towards drier conditions, even in regions and seasons where precipitation is projected to experience large increases (Figure 7.6) due to increases in the evapotranspiration associated with higher temperature. Drying is assessed to be large relative to natural variations in much of the CONUS region in the summer. Signifi- cant spring and fall drying is also projected in the mountainous western states, with poten- tial implications for forest and wildfire risk. Also, the combination of significant summer

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and fall drying in the midwestern states has potential agricultural implications. The largest percent changes are projected in the south-western United States and are consistent in magnitude with an earlier study of the Colorado River Basin using more sophisticated macroscale hydrological models.[42]

In this assessment, we limit the direct CMIP5 weighted multimodel projection of soil moisture shown in Figure 8.1 to the surface (defined as the top 10 cm of the soil), as the land surface component sub-models vary greatly in their representation of the total depth of the soil. A more relevant projection to agricultural drought would be the soil moisture at the root depth of typical U.S. crops. Cook et al.[38] find that future drying at a depth of 30 cm will be less than at 2 cm, but still significant and comparable to a modified PDSI formulation. Few of the CMIP5 land models have detailed ecological representations of evapotranspiration processes, causing the simulation of the soil moisture budget to be less constrained than reality.[61] Over the western United States, unrealistically low elevations in the CMIP5 models due to resolution constraints present a further challenge in interpreting evapotranspiration changes. Nonetheless, Figure 8.1 shows a projected drying of surface soil moisture across nearly all of the coterminous United States in all seasons, even in regions and seasons where
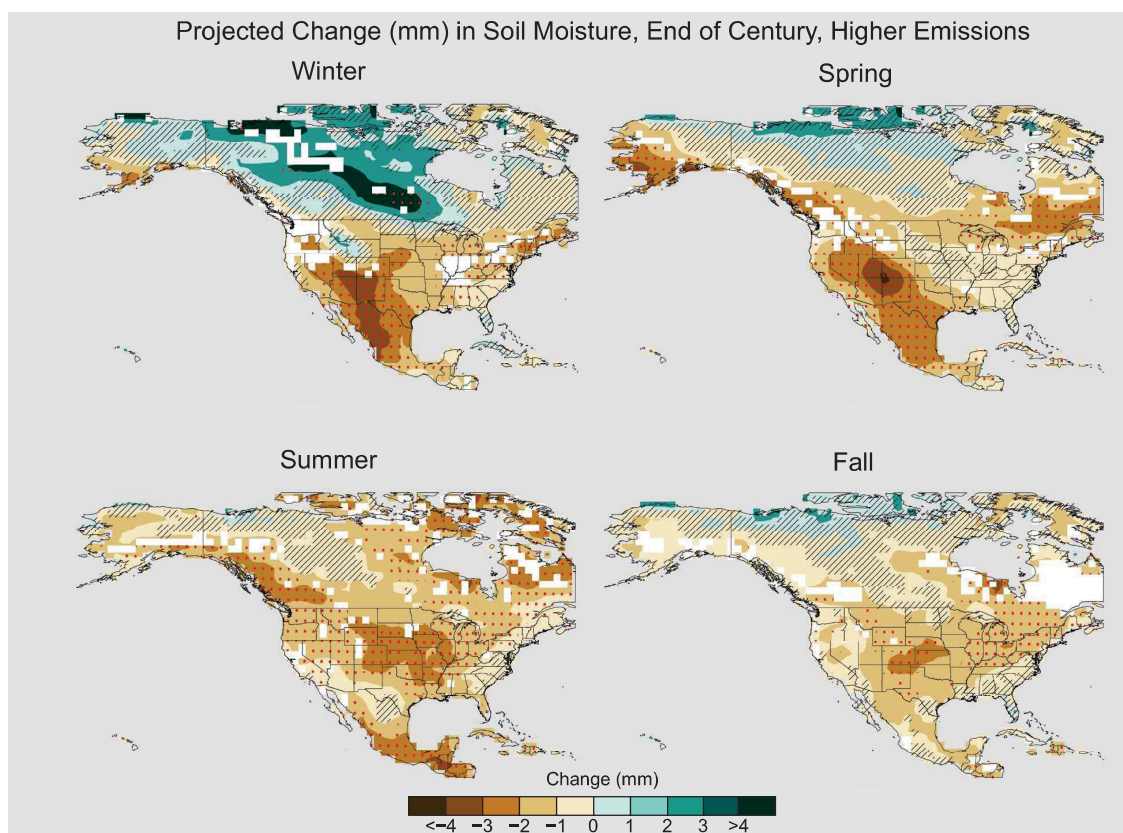


**Figure 8.1:** Projected end of the 21st century weighted CMIP5 multimodel average percent changes in near surface seasonal soil moisture (mrsos) under the higher scenario (RCP8.5). Stippling indicates that changes are assessed to be large compared to natural variations. Hashing indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI and CICS-NC).

precipitation is projected to increase, consistent with increased evapotranspiration due to elevated temperatures.[38]

Widespread reductions in mean snowfall across North America are projected by the CMIP5 models.[62] Together with earlier snowmelt at altitudes high enough for snow, disruptions in western U.S. water delivery systems are expected to lead to more frequent hydrological drought conditions.[40, 41, 50, 63, 64] Due to resolution constraints, the elevation of mountains as represented in the CMIP5 models is too low to adequately represent the effects of future temperature on snowpacks. However, increased model resolution has been demonstrated to have important impacts on future projections of snowpack water content in warmer climates and is enabled by recent advances in high performance computing.[65] Figure 8.2 and Table 8.2 show a projection of changes in western U.S. mountain winter (December, January, and February) hydrology obtained from a different high-resolution atmospheric model at the middle and end of the 21st century under the higher scenario (RCP8.5). These projections indicate dramatic reductions in all aspects of snow[66] and are similar to previous statistically downscaled pro-

jections.[67, 68] Table 8.2 reveals that the reductions in snow water equivalent accelerate in the latter half of this century under the higher scenario (RCP8.5) and with substantial variations across the western United States. Changes in snow residence time, an alternative measure of snowpack relevant to the timing of runoff, is also shown to be sensitive to elevation, with widespread reductions across this region.[69] Given the larger projected increases in temperature at high altitudes compared to adjacent lower altitudes[70] and the resulting changes in both snowpack depth and melt timing in very warm future scenarios such as RCP8.5, and assuming no change to water resource management practices, several important western U.S. snowpack reservoirs effectively disappear by 2100 in this dynamical projection, resulting in chronic, long-lasting hydrological drought. This dramatic statement is also supported by two climate model studies: a multimodel statistical downscaling of the CMIP5 RCP8.5 ensemble that finds large areal reductions in snow-dominated regions of the western United States by mid-century and complete elimination of snow-dominated regions in certain watersheds,[68] and a large ensemble simulation of a global climate model.[71]
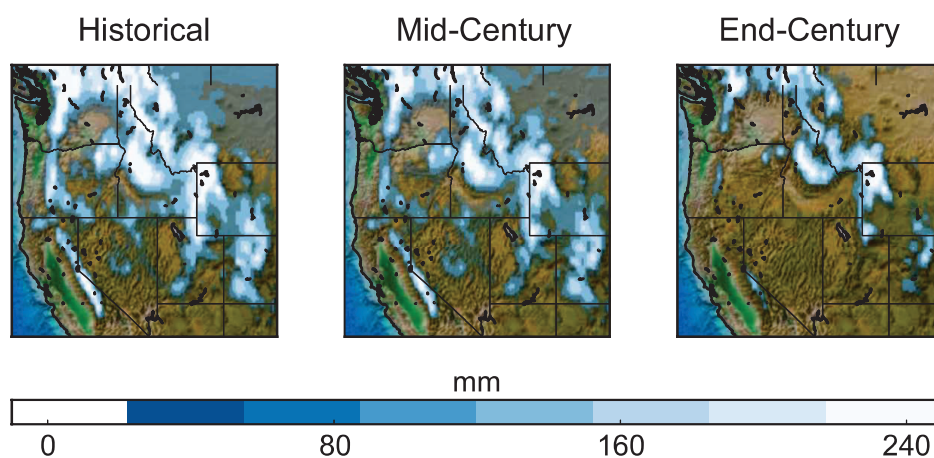


**Figure 8.2:** Projected changes in winter (DJF) snow water equivalent at the middle and end of this century under the higher scenario (RCP8.5) from a high-resolution version of the Community Atmospheric Model, CAM5.[66] (Figure source: H. Krishnan, LBNL).

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**Table 8.2.** Projected changes in western U.S. mountain range winter (DJF) snow-related hydrology variables at the middle and end of this century. Projections are for the higher scenario (RCP8.5) from a high-resolution version of the Community Atmospheric Model, CAM5.[66]

| Mountain Range | Snow Water Equivalent (% Change) | | Snow Cover (% Change) | | Snowfall (% Change) | | Surface Temperature (change in K) | |
|---|---|---|---|---|---|---|---|---|
| | 2050 | 2100 | 2050 | 2100 | 2050 | 2100 | 2050 | 2100 |
| Cascades | −41.5 | −89.9 | −21.6 | −72.9 | −10.7 | −50.0 | 0.9 | 4.1 |
| Klamath | −50.75 | −95.8 | −38.6 | −89.0 | −23.1 | −78.7 | 0.8 | 3.5 |
| Rockies | −17.3 | −65.1 | −8.2 | −43.1 | 1.7 | −8.2 | 1.4 | 5.5 |
| Sierra Nevada | −21.8 | −89.0 | −21.9 | −77.7 | −4.7 | −66.6 | 1.1 | 4.5 |
| Wasatch and Uinta | −18.9 | −78.7 | −14.2 | −61.4 | 4.1 | −34.6 | 1.8 | 6.1 |
| **Western USA** | **−22.3** | **−70.1** | **−12.7** | **−51.5** | **−1.6** | **−21.4** | **1.3** | **5.2** |

As earlier spring melt and reduced snow water equivalent have been formally attributed to human-induced warming, substantial reductions in western U.S. winter and spring snowpack are projected (with attribution) to be *very likely* as the climate continues to warm (*very high confidence*). Under higher scenarios and assuming no change to current water-resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

## 8.2 Floods

Flooding damage in the United States can come from flash floods of smaller rivers and creeks, prolonged flooding along major rivers, urban flooding unassociated with proximity to a riverway, coastal flooding from storm surge which may be exacerbated by sea level rise, and the confluence of coastal storms and inland riverine flooding from the same precipitation event (Ch. 12: Sea Level Rise). Flash flooding is associated with extreme precipitation somewhere along the river which may occur upstream of the regions at risk. Flooding of major rivers in the United States with substantial winter snow accumulations usually occurs in the late winter or spring and can result from an unusually heavy seasonal snowfall followed by a "rain on snow" event or from a rapid onset of higher temperatures that leads to rapid snow melting within the river basin. In the western coastal states, most flooding occurs in conjunction with extreme precipitation events referred to as "atmospheric rivers" (see Ch. 9: Extreme Storms),[72, 73] with mountain snowpack being vulnerable to these typically warmer-than-normal storms and their potential for rain on existing snow cover.[74] Hurricanes and tropical storms are an important driver of flooding events in the eastern United States. Changes in streamflow rates depend on many factors, both human and natural, in addition to climate change. Deforestation, urbanization, dams, floodwater management activities, and changes in agricultural practices can all play a role in past and future changes in flood statistics. Projection of future changes is thus a complex multivariate problem.[34]

The IPCC AR5[7] did not attribute changes in flooding to anthropogenic influence nor report detectable changes in flooding magnitude, duration, or frequency. Trends in extreme high values of streamflow are mixed across the United States.[34, 75, 76] Analysis of 200 U.S. stream gauges indicates areas of both increasing and decreasing flooding magnitude[77] but does not provide robust evidence that these trends are attributable to human influences. Significant increases in flood frequency have

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been detected in about one-third of stream gauge stations examined for the central United States, with a much stronger signal of frequency change than is found for changes in flood magnitude in these gauges.[78] This apparent disparity with ubiquitous increases in observed extreme precipitation (Figure 7.2) can be partly explained by the seasonality of the two phenomena. Extreme precipitation events in the eastern half of the CONUS are larger in the summer and fall when soil moisture and seasonal streamflow levels are low and less favorable for flooding.[79] By contrast, high streamflow events are often larger in the spring and winter when soil moisture is high and snowmelt and frozen ground can enhance runoff.[80] Furthermore, floods may be poorly explained by daily precipitation characteristics alone; the relevant mechanisms are more complex, involving processes that are seasonally and geographically variable, including the seasonal cycles of soil moisture content and snowfall/snowmelt.[81]

Recent analysis of annual maximum streamflow shows statistically significant trends in the upper Mississippi River valley (increasing) and in the Northwest (decreasing).[44] In fact, across the midwestern United States, statistically significant increases in flooding are well documented.[78, 82, 83, 84, 85, 86, 87, 88] These increases in flood risk and severity are not attributed to 20th century changes in agricultural practices[87, 89] but instead are attributed mostly to the observed increases in precipitation shown in Figures 7.1 through 7.4.[78, 84, 89, 90] Trends in maximum streamflow in the northeastern United States are less dramatic and less spatially coherent,[44, 80] although one study found mostly increasing trends[91] in that region, consistent with the increasing trends in observed extreme precipitation in the region (Ch. 6: Temperature Change).[34, 80]

The nature of the proxy archives complicates the reconstruction of past flood events in a gridded fashion as has been done with droughts. However, reconstructions of past river outflows do exist. For instance, it has been suggested that the mid-20th century water allocations from the Colorado River were made during one of the wettest periods of the past five centuries.[92] For the eastern United States, the Mississippi River has undergone century-scale variability in flood frequency—perhaps linked to the moisture availability in the central United States and the temperature structure of the Atlantic Ocean.[93]

The complex mix of processes complicates the formal attribution of observed flooding trends to anthropogenic climate change and suggests that additional scientific rigor is needed in flood attribution studies.[94] As noted above, precipitation increases have been found to strongly influence changes in flood statistics. However, in U.S. regions, no formal attribution of precipitation changes to anthropogenic forcing has been made so far, so indirect attribution of flooding changes is not possible. Hence, no formal attribution of observed flooding changes to anthropogenic forcing has been claimed.[78]

A projection study based on coupling an ensemble of regional climate model output to a hydrology model[95] finds that the magnitude of future very extreme runoff (which can lead to flooding) is decreased in most of the summer months in Washington State, Oregon, Idaho, and western Montana but substantially increases in the other seasons. Projected weighted increases in extreme runoff from the coast to the Cascade Mountains are particularly large in that study during the fall and winter which are not evident in the weighted seasonal averaged CMIP5 runoff projections.[2] For the West Coast of the United States, extremely heavy precipitation from intense atmospheric

river storms is an important factor in flood frequency and severity.[55, 96] Projections indicate greater frequency of heavy atmospheric rivers in the future (e.g., Dettinger et al. 2011;[96] Warner et al. 2015;[57] Gao et al. 2015;[58] see further discussion in Ch. 9: Extreme Storms). Translating these increases in atmospheric river frequency to their impact on flood frequency requires a detailed representation of western states topography in the global projection models and/or via dynamic downscaling to regional models and is a rapidly developing science. In a report prepared for the Federal Insurance and Mitigation Administration of the Federal Emergency Management Agency, a regression-based approach of scaling river gauge data based on seven commonly used climate change indices from the CMIP3 database[97] found that at the end of the 21st century the 1% annual chance floodplain area would increase in area by about 30%, with larger changes in the Northeast and Great Lakes regions and smaller changes in the central part of the country and the Gulf Coast.[98]

Urban flooding results from heavy precipitation events that overwhelm the existing sewer infrastructure's ability to convey the resulting stormwater. Future increases in daily and sub-daily extreme precipitation rates will require significant upgrades to many communities' storm sewer systems, as will sea level rise in coastal cities and towns.[99, 100]

No studies have formally attributed (see Ch. 3: Detection and Attribution) long-term changes in observed flooding of major rivers in the United States to anthropogenic forcing. We conclude that there is *medium confidence* that detectable (though not attributable to anthropogenic forcing changes) increases in flood statistics have occurred in parts of the central United States. Key Finding 3 of Chapter 7: Precipitation Change states that the frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century with *high confidence*. Given the connection between extreme precipitation and flooding, and the complexities of other relevant factors, we concur with the IPCC Special Report on Extremes (SREX) assessment of "medium confidence (based on physical reasoning) that projected increases in heavy rainfall would contribute to increases in local flooding in some catchments or regions".[101]

Existing studies of individual extreme flooding events are confined to changes in the locally responsible precipitation event and have not included detailed analyses of the events' hydrology. Gochis et al.[102] describe the massive floods of 2013 along the Colorado front range, estimating that the streamflow amounts ranged from 50- to 500-year return values across the region. Hoerling et al.[17] analyzed the 2013 northeastern Colorado heavy multiday precipitation event and resulting flood, finding little evidence of an anthropogenic influence on its occurrence. However, Pall et al.[103] challenge their event attribution methodology with a more constrained study and find that the thermodynamic response of precipitation in this event due to anthropogenic forcing was substantially increased. The Pall et al.[103] approach does not rule out that the likelihood of the extremely rare large-scale meteorological pattern responsible for the flood may have changed.

## 8.3 Wildfires

A global phenomenon with natural (lightning) and human-caused ignition sources, wildfire represents a critical ecosystem process. Recent decades have seen a profound increase in forest fire activity over the western United States and Alaska.[104, 105, 106, 107] The frequency of large wildfires is influenced by a complex combination of natural and human factors. Temperature, soil moisture, relative humidity, wind speed, and vegetation (fuel density) are

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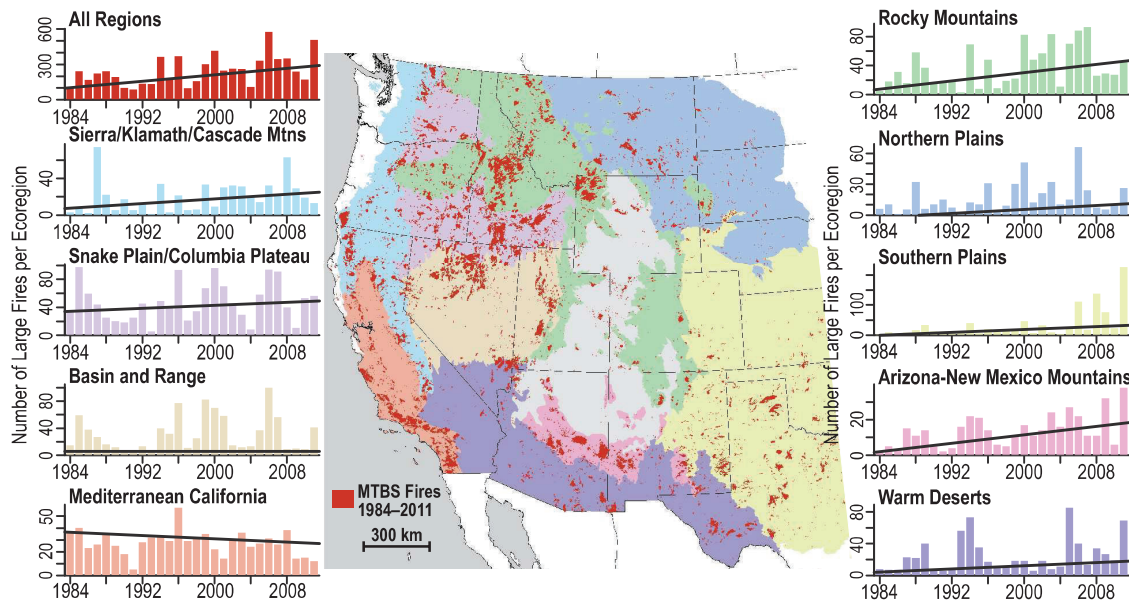
**Figure 8.3:** Trends in the annual number of large fires in the western United States for a variety of ecoregions. The black lines are fitted trend lines. Statistically significant at a 10% level for all regions except the Snake Plain/Columbian Plateau, Basin and Range, and Mediterranean California regions. (Figure source: Dennison et al.[108]).

important aspects of the relationship between fire frequency and ecosystems. Forest management and fire suppression practices can also alter this relationship from what it was in the preindustrial era. Changes in these control parameters can interact with each other in complex ways with the potential for tipping points—in both fire frequency and in ecosystem properties—that may be crossed as the climate warms.

Figure 8.3 shows that the number of large fires has increased over the period 1984–2011, with high statistical significance in 7 out of 10 western U.S. regions across a large variety of vegetation, elevation, and climatic types.[108] State-level fire data over the 20th century[109] indicates that area burned in the western United States decreased from 1916 to about 1940, was at low levels until the 1970s, then increased into the more recent period. Modeled increases in temperatures and vapor pressure deficits due to anthropogenic climate change have increased forest fire activity in the western United States by increasing the aridity of forest fu-

els during the fire season.[104] Increases in these relevant climatic drivers were found to be responsible for over half the observed increase in western U.S. forest fuel aridity from 1979 to 2015 and doubled the forest fire area over the period 1984–2015.[104] Littell et al. (2009, 2010, 2016)[109, 110, 111] found that two climatic mechanisms affect fire in the western United States: increased fuel flammability driven by warmer, drier conditions and increased fuel availability driven by antecedent moisture. Littell et al.[111] found a clear link between increased drought and increased fire risk. Yoon et al.[112] assessed the 2014 fire season, finding an increased risk of fire in California. While fire suppression practices can also lead to a significant increase in fire risk in lower-elevation and drier forest types, this is less important in higher-elevation and moister forests.[113, 114, 115] Increases in future forest fire extent, frequency, and intensity depend strongly on local ecosystem properties and will vary greatly across the United States. Westerling et al.[116] projected substantial increases in forest fire frequency in the Greater Yellowstone ecosystem by mid-century under

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the older SRES A2 emissions scenario, and further stated that years without large fires in the region will become extremely rare. Stavros et al.[117] projected increases in very large fires (greater than 50,000 acres) across the western United States by mid-century under both the lower and higher scenarios (RCP4.5 and RCP8.5, respectively). Likewise, Prestemon et al.[118] projected significant increases in lightning-ignited wildfire in the Southeast by mid-century but with substantial differences between ecoregions. However, other factors, related to climate change such as water scarcity or insect infestations may act to stifle future forest fire activity by reducing growth or otherwise killing trees leading to fuel reduction.[110]

Historically, wildfires have been less frequent and of smaller extent in Alaska compared to the rest of the globe.[119, 120] Shortened land snow cover seasons and higher temperatures have made the Arctic more vulnerable to wildfire.[119, 120, 121] Total area burned and the number of large fires (those with area greater than 1,000 square km or 386 square miles) in Alaska exhibits significant interannual and decadal scale variability from influences of atmospheric circulation patterns and controlled burns, but have *likely* increased since 1959.[122] The most recent decade has seen an unusually large number of severe wildfire years in Alaska, for which the risk of severe fires has *likely* increased by 33%–50% as a result of anthropogenic climate change[123] and is projected to increase by up to a factor of four by the end of the century under the mid-high scenario (RCP6.0).[121] Historically less flammable tundra and cooler boreal forest regions could shift into historically unprecedented fire risk regimes as a consequence of temperatures increasing above the minimum thresholds required for burning. Alaska's fire season is also *likely* lengthening—a trend expected to continue.[119, 124] Thresholds in temperature and precipitation shape Arctic fire regimes, and

projected increases in future lightning activity imply increased vulnerability to future climate change.[119, 121] Alaskan tundra and forest wildfires will *likely* increase under warmer and drier conditions[124, 125] and potentially result in a transition into a fire regime unprecedented in the last 10,000 years.[126] Total area burned is projected to increase between 25% and 53% by the end of the century.[127]

Boreal forests and tundra contain large stores of carbon, approximately 50% of the total global soil carbon.[128] Increased fire activity could deplete these stores, releasing them to the atmosphere to serve as an additional source of atmospheric $CO_2$ and alter the carbon cycle if ecosystems change from higher to lower carbon densities.[126, 128] Additionally, increased fires in Alaska may also enhance the degradation of Alaska's permafrost, blackening the ground, reducing surface albedo, and removing protective vegetation.

Both anthropogenic climate change and the legacy of land use/management have an influence on U.S. wildfires and are subtly and inextricably intertwined. Forest management practices have resulted in higher fuel densities in most U.S. forests, except in the Alaskan bush and the higher mountainous regions of the western United States. Nonetheless, there is *medium confidence* for a human-caused climate change contribution to increased forest fire activity in Alaska in recent decades with a *likely* further increase as the climate continues to warm, and *low to medium confidence* for a detectable human climate change contribution in the western United States based on existing studies. Recent literature does not contain a complete robust detection and attribution analysis of forest fires including estimates of natural decadal and multidecadal variability, as described in Chapter 3: Detection and Attribution, nor separate the contributions to observed trends from climate change and for-

est management. These assessment statements about attribution to human-induced climate change are instead multistep attribution statements (Ch. 3: Detection and Attribution) based on plausible model-based estimates of anthropogenic contributions to observed trends. The modeled contributions, in turn, are based on climate variables that are closely linked to fire risk and that, in most cases, have a detectable human influence, such as surface air temperature and snow melt timing.

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## TRACEABLE ACCOUNTS

### Key Finding 1

Recent droughts and associated heat waves have reached record intensity in some regions of the United States; however, by geographical scale and duration, the Dust Bowl era of the 1930s remains the benchmark drought and extreme heat event in the historical record (*very high confidence*). While by some measures drought has decreased over much of the continental United States in association with long-term increases in precipitation, neither the precipitation increases nor inferred drought decreases have been confidently attributed to anthropogenic forcing.

### Description of evidence base

Recent droughts are well characterized and described in the literature. The Dust Bowl is not as well documented, but available observational records support the key finding. The last sentence is an "absence of evidence" statement and does not imply "evidence of absence" of future anthropogenic changes. The inferred decreases in some measures of U.S. drought or types of drought (heat wave/flash droughts) are described in Andreadis and Lettenmaier[12] and Mo and Lettenmaier[3].

### Major uncertainties

Record-breaking temperatures are well documented with low uncertainty.[129] The magnitude of the Dust Bowl relative to present times varies with location. Uncertainty in the key finding is affected by the quality of pre-World War II observations but is relatively low.

### Assessment of confidence based on evidence and agreement

Precipitation is well observed in the United States, leading to *very high confidence*.

### Summary sentence or paragraph that integrates the above information

The key finding is a statement that recent U.S. droughts, while sometimes long and severe, are not unprecedented in the historical record.

### Key Finding 2

The human effect on recent major U.S. droughts is complicated. Little evidence is found for a human influence on observed precipitation deficits, but much evidence is found for a human influence on surface soil moisture deficits due to increased evapotranspiration caused by higher temperatures (*high confidence*).

### Description of evidence base

Observational records of meteorological drought are not long enough to detect statistically significant trends. Additionally, paleoclimatic evidence suggests that major droughts have occurred throughout the distant past. Surface soil moisture is not well observed throughout the CONUS, but numerous event attribution studies attribute enhanced reduction of surface soil moisture during dry periods to anthropogenic warming and enhanced evapotranspiration. Sophisticated land surface models have been demonstrated to reproduce the available observations and have allowed for century scale reconstructions.

### Major uncertainties

Uncertainties stem from the length of precipitation observations and the lack of surface moisture observations.

### Assessment of confidence based on evidence and agreement

Confidence is *high* for widespread future surface soil moisture deficits, as little change is projected for future summer and fall average precipitation. In the absence of increased precipitation (and in some cases with it), evapotranspiration increases due to increased temperatures will lead to less soil moisture overall, especially near the surface.

### Summary sentence or paragraph that integrates the above information

The precipitation deficit portion of the key finding is a conservative statement reflecting the conflicting and limited event attribution literature on meteorological drought. The soil moisture portion of the key finding is limited to the surface and not the more relevant root depth and is supported by the studies cited in this chapter.

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**Key Finding 3**

Future decreases in surface (top 10 cm) soil moisture from anthropogenic forcing over most of the United States are *likely* as the climate warms under the higher scenarios. (*Medium confidence*)

**Description of evidence base**

First principles establish that evaporation is at least linearly dependent on temperatures and accounts for much of the surface moisture decrease as temperature increases. Plant transpiration for many non-desert species controls plant temperature and responds to increased temperature by opening stomata to release more water vapor. This water comes from the soil at root depth as the plant exhausts its stored water supply (*very high confidence*). Furthermore, nearly all CMIP5 models exhibit U.S. surface soil moisture drying at the end of the century under the higher scenario (RCP8.5), and the multimodel average exhibits no significant annual soil moisture increases anywhere on the planet.[2]

**Major uncertainties**

While both evaporation and transpiration changes are of the same sign as temperature increases, the relative importance of each as a function of depth is less well quantified. The amount of transpiration varies considerably among plant species, and these are treated with widely varying degrees of sophistication in the land surface components of contemporary climate models. Uncertainty in the sign of the anthropogenic change of root depth soil moisture is low in regions and seasons of projected precipitation decreases (Ch. 7: Precipitation Changes). There is moderate to high uncertainty in the magnitude of the change in soil moisture at all depths and all regions and seasons. This key finding is a "projection without attribution" statement as such a drying is not part of the observed record. Projections of summertime mean CONUS precipitation exhibit no significant change. However, recent summertime precipitation trends are positive, leading to reduced agricultural drought conditions overall.[12] While statistically significant increases in precipitation have been identified over parts of the United States, these trends have not been clearly attributed to anthropogenic forcing (Ch. 7: Precipitation Change). Furthermore, North

American summer temperature increases under the higher scenario (RCP8.5) at the end of the century are projected to be substantially more than the current observed (and modeled) temperature increase. Because of the response of evapotranspiration to temperature increases, the CMIP5 multimodel average projection is for drier surface soils even in those high latitude regions (Alaska and Canada) that are confidently projected to experience increases in precipitation. Hence, in the CONUS region, with little or no projected summertime changes in precipitation, we conclude that surface soil moisture will *likely* decrease.

**Assessment of confidence based on evidence and agreement**

CMIP5 and regional models support the surface soil moisture key finding. Confidence is assessed as "medium" as this key finding—despite the high level of agreement among model projections—because of difficulties in observing long-term changes in this metric, and because, at present, there is no published evidence of detectable long-term decreases in surface soil moisture across the United States.

**Summary sentence or paragraph that integrates the above information**

In the northern United States, surface soil moisture (top 10 cm) is *likely* to decrease as evaporation outpaces increases in precipitation. In the Southwest, the combination of temperature increases and precipitation decreases causes surface soil moisture decreases to be *very likely*. In this region, decreases in soil moisture at the root depth are *likely*.

**Key Finding 4**

Substantial reductions in western U.S. winter and spring snowpack are projected as the climate warms. Earlier spring melt and reduced snow water equivalent have been formally attributed to human induced warming (*high confidence*) and will *very likely* be exacerbated as the climate continues to warm (*very high confidence*). Under higher scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible by the end of this century (*very high confidence*).

**Description of evidence base**

First principles tell us that as temperatures rise, minimum snow levels also must rise. Certain changes in western U.S. hydrology have already been attributed to human causes in several papers following Barnett et al.[41] and are cited in the text. The CMIP3/5 models project widespread warming with future increases in atmospheric GHG concentrations, although these are underestimated in the current generation of global climate models (GCMs) at the high altitudes of the western United States due to constraints on orographic representation at current GCM spatial resolutions.

CMIP5 models were not designed or constructed for direct projection of locally relevant snowpack amounts. However, a high-resolution climate model, selected for its ability to simulate western U.S. snowpack amounts and extent, projects devastating changes in the hydrology of this region assuming constant water resource management practices.[66] This conclusion is also supported by a statistical downscaling result shown in Figure 3.1 of Walsh et al.[34] and Cayan et al.[67] and by the more recent statistical downscaling study of Klos et al.[68].

**Major uncertainties**

The major uncertainty is not so much "if" but rather "how much" as changes to precipitation phases (rain or snow) are sensitive to temperature increases that in turn depend on greenhouse gas (GHG) forcing changes. Also, changes to the lower-elevation catchments will be realized prior to those at higher elevations that, even at 25 km, are not adequately resolved. Uncertainty in the final statement also stems from the usage of one model but is tempered by similar findings from statistical downscaling studies. However, this simulation is a so-called "prescribed temperature" experiment with the usual uncertainties about climate sensitivity wired in by the usage of one particular ocean temperature change. Uncertainty in the equator-to-pole differential ocean warming rate is also a factor.

**Assessment of confidence based on evidence and agreement**

All CMIP5 models project large-scale warming in the western United States as GHG forcing increases. Warm-

ing is underestimated in most of the western United States due to elevation deficiencies that are a consequence of coarse model resolution.

**Summary sentence or paragraph that integrates the above information**

Warmer temperatures lead to less snow and more rain if total precipitation remains unchanged. Projected winter/spring precipitation changes are a mix of increases in northern states and decreases in the Southwest. In the northern Rocky Mountains, snowpack is projected to decrease even with a projected precipitation increase due to this phase change effect. This will lead to, at the very least, profound changes to the seasonal and sub-seasonal timing of the western U.S. hydrological cycle even where annual precipitation remains nearly unchanged with a strong potential for water shortages.

**Key Finding 5**

Detectable changes in some classes of flood frequency have occurred in parts of the United States and are a mix of increases and decreases. Extreme precipitation, one of the controlling factors in flood statistics, is observed to have generally increased and is projected to continue to do so across the United States in a warming atmosphere. However, formal attribution approaches have not established a significant connection of increased riverine flooding to human-induced climate change, and the timing of any emergence of a future detectible anthropogenic change in flooding is unclear. (*Medium confidence*)

**Description of evidence base**

Observed changes are a mix of increases and decreases and are documented by Walsh et al.[34] and other studies cited in the text. No attribution statements have been made.

**Major uncertainties**

Floods are highly variable both in space and time. The multivariate nature of floods complicates detection and attribution.

**Assessment of confidence based on evidence and agreement**

Confidence is limited to *medium* due to both the lack of an attributable change in observed flooding to date and the complicated multivariate nature of flooding. However, confidence is *high* in the projections of increased future extreme precipitation, the principal driver (among several) of many floods. It is unclear when an observed long-term increase in U.S. riverine flooding will be attributed to anthropogenic climate change. Hence, confidence is *medium* in this part of the key message at this time.

**Summary sentence or paragraph that integrates the above information**

The key finding is a relatively weak statement reflecting the lack of definitive detection and attribution of anthropogenic changes in U.S. flooding intensity, duration, and frequency.

**Key Finding 6**

The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s (*high confidence*) and is projected to further increase in those regions as the climate warms with profound changes to certain ecosystems (*medium confidence*).

**Description of evidence base**

Studies by Dennison et al. (western United States)[108] and Kasischke and Turetsky (Alaska)[122] document the observed increases in fire statistics. Projections of Westerling et al. (western United States)[116] and Young et al.[121] and others (Alaska) indicate increased fire risk. These observations and projections are consistent with drying due to warmer temperatures leading to increased flammability and longer fire seasons.

**Major uncertainties**

Analyses of other regions of the United States, which also could be subject to increased fire risk, do not seem to be readily available. Likewise, projections of the western U.S. fire risk are of limited areas. In terms of attribution, there is still some uncertainty as to how well non-climatic confounding factors such as forestry management and fire suppression practices have been accounted for, particularly for the western United States. Other climate change factors, such as increased water deficits and insect infestations, could reduce fuel loads, tending towards reducing fire frequency and/or intensity.

**Assessment of confidence based on evidence and agreement**

Confidence is *high* in the observations due to solid observational evidence. Confidence in projections would be higher if there were more available studies covering a broader area of the United States and a wider range of ecosystems.

**Summary sentence or paragraph that integrates the above information**

Wildfires have increased over parts of the western United States and Alaska in recent decades and are projected to continue to increase as a result of climate change. As a result, shifts in certain ecosystem types may occur.

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# 9

# Extreme Storms

## KEY FINDINGS

1. Human activities have contributed substantially to observed ocean–atmosphere variability in the Atlantic Ocean (*medium confidence*), and these changes have contributed to the observed upward trend in North Atlantic hurricane activity since the 1970s (*medium confidence*).

2. Both theory and numerical modeling simulations generally indicate an increase in tropical cyclone (TC) intensity in a warmer world, and the models generally show an increase in the number of very intense TCs. For Atlantic and eastern North Pacific hurricanes and western North Pacific typhoons, increases are projected in precipitation rates (*high confidence*) and intensity (*medium confidence*). The frequency of the most intense of these storms is projected to increase in the Atlantic and western North Pacific (*low confidence*) and in the eastern North Pacific (*medium confidence*).

3. Tornado activity in the United States has become more variable, particularly over the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days (*medium confidence*). Confidence in past trends for hail and severe thunderstorm winds, however, is *low*. Climate models consistently project environmental changes that would putatively support an increase in the frequency and intensity of severe thunderstorms (a category that combines tornadoes, hail, and winds), especially over regions that are currently prone to these hazards, but confidence in the details of this projected increase is *low*.

4. There has been a trend toward earlier snowmelt and a decrease in snowstorm frequency on the southern margins of climatologically snowy areas (*medium confidence*). Winter storm tracks have shifted northward since 1950 over the Northern Hemisphere (*medium confidence*). Projections of winter storm frequency and intensity over the United States vary from increasing to decreasing depending on region, but model agreement is poor and confidence is *low*. Potential linkages between the frequency and intensity of severe winter storms in the United States and accelerated warming in the Arctic have been postulated, but they are complex, and, to some extent, contested, and confidence in the connection is currently *low*.

5. The frequency and severity of landfalling "atmospheric rivers" on the U.S. West Coast (narrow streams of moisture that account for 30%–40% of the typical snowpack and annual precipitation in the region and are associated with severe flooding events) will increase as a result of increasing evaporation and resulting higher atmospheric water vapor that occurs with increasing temperature. (*Medium confidence*)

## 9.1 Introduction

Extreme storms have numerous impacts on lives and property. Quantifying how broad-scale average climate influences the behavior of extreme storms is particularly challenging, in part because extreme storms are comparatively rare short-lived events and occur within an environment of largely random variability. Additionally, because the physical mechanisms linking climate change and extreme storms can manifest in a variety of ways, even the sign of the changes in the extreme storms can vary in a warming climate. This makes detection and attribution of trends in extreme storm characteristics more difficult than detection and attribution of trends in the larger environment in which the storms evolve (e.g., Ch. 6: Temperature Change). Projecting changes in severe storms is also challenging because of model constraints in how they capture and represent small-scale, highly local physics. Despite the challenges, good progress is being made for a variety of storm types, such as tropical cyclones, severe convective storms (thunderstorms), winter storms, and atmospheric river events.

## 9.2 Tropical Cyclones (Hurricanes and Typhoons)

Detection and attribution (Ch. 3: Detection and Attribution) of past changes in tropical cyclone (TC) behavior remain a challenge due to the nature of the historical data, which are highly heterogeneous in both time and among the various regions that collect and analyze the data.[1, 2, 3] While there are ongoing efforts to reanalyze and homogenize the data (e.g., Landsea et al. 2015;[4] Kossin et al. 2013[2]), there is still low confidence that any reported long-term (multidecadal to centennial) increases in TC activity are robust, after accounting for past changes in observing capabilities [which is unchanged from the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) assessment statement[5]]. This is not meant to

imply that no such increases have occurred, but rather that the data are not of a high enough quality to determine this with much confidence. Furthermore, it has been argued that within the period of highest data quality (since around 1980), the globally observed changes in the environment would not necessarily support a detectable trend in tropical cyclone intensity.[2] That is, the trend signal has not yet had time to rise above the background variability of natural processes.

Both theory and numerical modeling simulations (in general) indicate an increase in TC intensity in a warmer world, and the models generally show an increase in the number of very intense TCs.[6, 7, 8, 9, 10] In some cases, climate models can be used to make attribution statements about TCs without formal detection (see also Ch. 3: Detection and Attribution). For example, there is evidence that, in addition to the effects of El Niño, anthropogenic forcing made the extremely active 2014 Hawaiian hurricane season substantially more likely, although no significant rising trend in TC frequency near Hawai'i was detected.[11]

Changes in frequency and intensity are not the only measures of TC behavior that may be affected by climate variability and change, and there is evidence that the locations where TCs reach their peak intensity has migrated poleward over the past 30 years in the Northern and Southern Hemispheres, apparently in concert with environmental changes associated with the independently observed expansion of the tropics.[12] The poleward migration in the western North Pacific,[13] which includes a number of U.S. territories, appears particularly consistent among the various available TC datasets and remains significant over the past 60–70 years after accounting for the known modes of natural variability in the region (Figure 9.1). The migration, which can substantially change patterns of TC hazard exposure and

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mortality risk, is also evident in 21st century Coupled Model Intercomparison Project Phase 5 (CMIP5) projections following the RCP8.5 emissions trajectories, suggesting a possible link to human activities. Further analysis comparing observed past TC behavior with climate model historical forcing runs (and with model control runs simulating multidecadal internal climate variability alone) are needed to better understand this process, but it is expected that this will be an area of heightened future research.

In the Atlantic, observed multidecadal variability of the ocean and atmosphere, which TCs are shown to respond to, has been ascribed (Ch. 3: Detection and Attribution) to natural internal variability via meridional overturning ocean circulation changes,[14] natural external variability caused by volcanic eruptions[15, 16] and Saharan dust outbreaks,[17, 18] and anthropogenic ex-

ternal forcing via greenhouse gases and sulfate aerosols.[19, 20, 21] Determining the relative contributions of each mechanism to the observed multidecadal variability in the Atlantic, and even whether natural or anthropogenic factors have dominated, is presently a very active area of research and debate, and no consensus has yet been reached.[22, 23, 24, 25, 26, 27] Despite the level of disagreement about the relative magnitude of human influences, there is broad agreement that human factors have had an impact on the observed oceanic and atmospheric variability in the North Atlantic, and there is *medium confidence* that this has contributed to the observed increase in hurricane activity since the 1970s. This is essentially unchanged from the IPCC AR5 statement,[6] although the post-AR5 literature has only served to further support this statement.[28] This is expected to remain an active research topic in the foreseeable future.
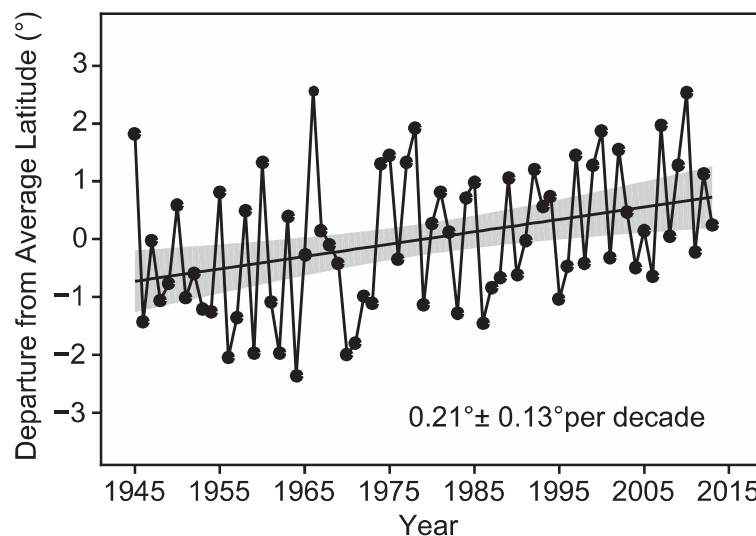


**Figure 9.1:** Poleward migration, in degrees of latitude, of the location of annual mean tropical cyclone (TC) peak lifetime intensity in the western North Pacific Ocean, after accounting for the known regional modes of interannual (El Niño–Southern Oscillation; ENSO) and interdecadal (Pacific Decadal Oscillation; PDO) variability. The time series shows residuals of the multivariate regression of annually averaged latitude of TC peak lifetime intensity onto the mean Niño-3.4 and PDO indices. Data are taken from the Joint Typhoon Warning Center (JTWC). Shading shows 95% confidence bounds for the trend. Annotated values at lower right show the mean migration rate and its 95% confidence interval in degrees per decade for the period 1945–2013. (Figure source: adapted from Kossin et al. 2016;[13] © American Meteorological Society. Used with permission.)
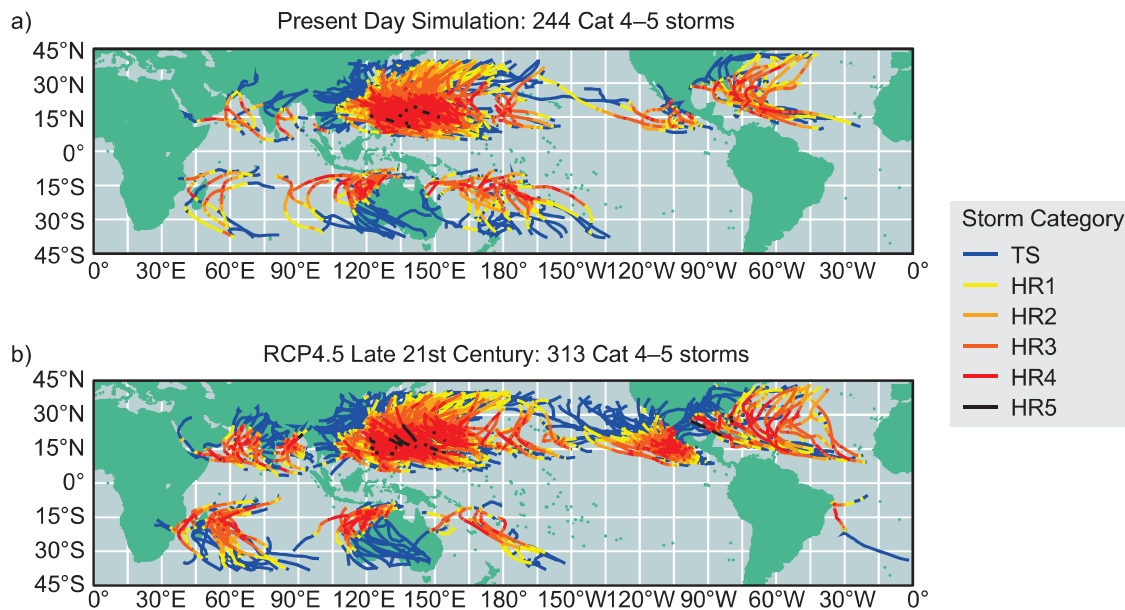
The IPCC AR5 consensus TC projections for the late 21st century (IPCC Figure 14.17)[8] include an increase in global mean TC intensity, precipitation rate, and frequency of very intense (Saffir-Simpson Category 4–5) TCs, and a decrease, or little change, in global TC frequency. Since the IPCC AR5, some studies have provided additional support for this consensus, and some have challenged an aspect of it. For example, a recent study[9] projects increased mean hurricane intensities in the Atlantic Ocean basin and in most, but not all, other TC-supporting basins (see Table 3 in Knutson et al. 2015[9]). In their study, the global occurrence of Saffir–Simpson Category 4–5 storms was projected to increase significantly, with the most significant basin-scale changes projected for the Northeast Pacific basin, potentially increasing intense hurricane risk to Hawai'i (Figure 9.2) over the coming century. However, another recent (post-AR5) study proposed that increased thermal stratification of the upper ocean in CMIP5 climate warming scenarios should substantially reduce the warming-induced intensification of TCs estimated in previous studies.[29] Follow-up studies, however, estimate that the effect of such increased stratification is relatively small, reducing the projected intensification of TCs by only about 10%–15%.[30, 31]

Another recent study challenged the IPCC AR5 consensus projection of a decrease, or little change, in global tropical cyclone frequency by simulating increased global TC frequency over the 21st century under the higher scenario (RCP8.5).[32] However, another modeling study has found that neither direct analysis of CMIP5-class simulations, nor indirect inferences from the simulations (such as those of Emanuel 2013[32]), could reproduce the decrease in TC frequency projected in a warmer world by high-resolution TC-permitting climate models,[33] which adds uncertainty to the results of Emanuel.[32]

In summary, despite new research that challenges one aspect of the AR5 consensus for late 21st century-projected TC activity, it remains *likely* that global mean tropical cyclone maximum wind speeds and precipitation rates will increase; and it is *more likely than not* that the global frequency of occurrence of TCs will either decrease or remain essentially the same. Confidence in projected global increases of intensity and tropical cyclone precipitation rates is *medium* and *high*, respectively, as there is better model consensus. Confidence is further heightened, particularly for projected increases in precipitation rates, by a robust physical understanding of the processes that lead to these increases. Confidence in projected increases in the frequency of very intense TCs is generally lower (*medium* in the eastern North Pacific and *low* in the western North Pacific and Atlantic) due to comparatively fewer studies available and due to the competing influences of projected reductions in overall storm frequency and increased mean intensity on the frequency of the most intense storms. Both the magnitude and sign of projected changes in individual ocean basins appears to depend on the large-scale pattern of changes to atmospheric circulation and ocean surface temperature (e.g., Knutson et al. 2015[9]). Projections of these regional patterns of change—apparently critical for TC projections—are uncertain, leading to uncertainty in regional TC projections.

a)
Present Day Simulation: 244 Cat 4–5 storms

b)
RCP4.5 Late 21st Century: 313 Cat 4–5 storms



Storm Category
— TS
— HR1
— HR2
— HR3
— HR4
— HR5

**Figure 9.2:** Tracks of simulated Saffir–Simpson Category 4–5 tropical cyclones for (a) present-day or (b) late-21st-century conditions, based on dynamical downscaling of climate conditions from the CMIP5 multimodel ensemble (lower scenario; RCP4.5). The tropical cyclones were initially simulated using a 50-km grid global atmospheric model, but each individual tropical cyclone was re-simulated at higher resolution using the GFDL hurricane model to provide more realistic storm intensities and structure. Storm categories or intensities are shown over the lifetime of each simulated storm, according to the Saffir–Simpson scale. The categories are depicted by the track colors, varying from tropical storm (blue) to Category 5 (black; see legend). (Figure source: Knutson et al. 2015;[9] © American Meteorological Society. Used with permission.)

## Box 9.1: U.S. Landfalling Major Hurricane "Drought"

Hurricane Harvey made landfall as a major hurricane (Saffir–Simpson Category 3 or higher) in Texas in 2017, breaking what has sometimes been colloquially referred to as the "hurricane drought." Prior to Harvey, the last major hurricane to make landfall in the continental United States was Wilma in 2005. The 11-year (2006–2016) absence of U.S. major hurricane landfall events is unprecedented in the historical records dating back to the mid-19th century and has occurred in tandem with average to above-average basin-wide major hurricane counts. Was the 11-year absence of U.S. landfalling major hurricanes due to random luck, or were there systematic changes in climate that drove this?

One recent study indicates that the absence of U.S. landfalling major hurricanes cannot readily be attributed to any sustained changes in the climate patterns that affect hurricanes.[34] Based on a statistical analysis of the historical North Atlantic hurricane database, the study found no evidence of a connection between the number of major U.S. landfalls from one year to the next and concluded that the 11-year absence of U.S. landfalling major hurricanes was random. A subsequent recent study did identify a systematic pattern of atmosphere/ocean conditions that vary in such a way that conditions conducive to hurricane intensification in the deep tropics occur in concert with conditions conducive to weakening near the U.S. coast.[35] This result suggests a possible relationship between climate and hurricanes; increasing basin-wide hurricane counts are associated with a decreasing fraction of major hurricanes making U.S. landfall, as major hurricanes approaching the U.S. coast are more likely to

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## Box 9.1 (*continued*)

weaken during active North Atlantic hurricane periods (such as the present period). It is unclear to what degree this relationship has affected absolute hurricane landfall counts during the recent active hurricane period from the mid-1990s, as the basin-wide number and landfalling fraction are in opposition (that is, there are more major hurricanes but a smaller fraction make landfall as major hurricanes). It is also unclear how this relationship may change as the climate continues to warm. Other studies have identified systematic interdecadal hurricane track variability that may affect landfalling hurricane and major hurricane frequency.[36, 37, 38]

Another recent study[39] shows that the extent of the absence is sensitive to uncertainties in the historical data and even small variations in the definition of a major hurricane, which is somewhat arbitrary. It is also sensitive to the definition of U.S. landfall, which is a geopolitical-border-based constraint and has no physical meaning. In fact, many areas outside of the U.S. border have experienced major hurricane landfalls in the past 11 years. In this sense, the frequency of U.S. landfalling major hurricanes is not a particularly robust metric with which to study questions about hurricane activity and its relationship with climate variability. Furthermore, the 11-year absence of U.S. landfalling major hurricanes is not a particularly relevant metric in terms of coastal hazard exposure and risk. For example, Hurricanes Ike (2008), Irene (2011), Sandy (2012), and most recently Hurricane Matthew (2016) brought severe impacts to the U.S. coast despite not making landfall in the United States while classified as major hurricanes. In the case of Hurricane Sandy, extreme rainfall and storm surge (see also Ch. 12: Sea Level Rise) during landfall caused extensive destruction in and around the New York City area, despite Sandy's designation as a post-tropical cyclone at that time. In the case of Hurricane Matthew, the center came within about 40 miles of the Florida coast while Matthew was a major hurricane, which is close enough to significantly impact the coast but not close enough to break the "drought" as it is defined.

In summary, the absence of U.S. landfalling major hurricanes from Wilma in 2005 to Harvey in 2017 was anomalous. There is some evidence that systematic atmosphere/ocean variability has reduced the fraction of hurricanes making U.S. landfall since the mid-1990s, but this is at least partly countered by increased basin-wide numbers, and the net effect on landfall rates is unclear. Moreover, there is a large random element, and the metric itself suffers from lack of physical basis due to the arbitrary intensity threshold and geopolitically based constraints. Additionally, U.S. coastal risk, particularly from storm surge and freshwater flooding, depends strongly on storm size, propagation speed and direction, and rainfall rates. There is some danger, in the form of evoking complacency, in placing too much emphasis on an absence of a specific subset of hurricanes.

## 9.3 Severe Convective Storms (Thunderstorms)

Tornado and severe thunderstorm events cause significant loss of life and property: more than one-third of the $1 billion weather disasters in the United States during the past 25 years were due to such events, and, relative to other extreme weather, the damages from convective weather hazards have undergone the largest increase since 1980.[40] A particular challenge in quantifying the existence and intensity of these events arises from the data source: rather than measurements, the occurrence of tornadoes and severe thunderstorms is determined by visual sightings by eyewitnesses (such as "storm spotters" and law enforcement officials) or post-storm damage assessments. The reporting has been susceptible to changes in population density, modifications to reporting procedures and training, the introduction of video and social media, and so on. These have led to systematic, non-meteorological biases in the long-term data record.

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Nonetheless, judicious use of the report database has revealed important information about tornado trends. Since the 1970s, the United States has experienced a decrease in the number of days per year on which tornadoes occur, but an increase in the number of tornadoes that form on such days.[41] One important implication is that the frequency of days with large numbers of tornadoes—tornado outbreaks—appears to be increasing (Figure 9.3). The extent of the season over which such tornado activity occurs is increasing as well: although tornadoes in the United States are observed in all months of the year, an earlier calendar-day start to the season of high activity is emerging. In general, there is more interannual variability, or volatility, in tornado occurrence (see also Elsner et al. 2015[42]).[43]

Evaluations of hail and (non-tornadic) thunderstorm wind reports have thus far been less revealing. Although there is evidence of an increase in the number of hail days per year, the inherent uncertainty in reported hail size reduces the confidence in such a conclusion.[44]

Thunderstorm wind reports have proven to be even less reliable, because, as compared to tornadoes and hail, there is less tangible visual evidence; thus, although the United States has lately experienced several significant thunderstorm wind events (sometimes referred to as "derechos"), the lack of studies that explore long-term trends in wind events and the uncertainties in the historical data preclude any robust assessment.

It is possible to bypass the use of reports by exploiting the fact that the temperature, humidity, and wind in the larger vicinity—or "environment"—of a developing thunderstorm ultimately control the intensity, morphology, and hazardous tendency of the storm. Thus, the premise is that quantifications of the vertical profiles of temperature, humidity, and wind can be used as a proxy for actual severe thunderstorm occurrence. In particular, a thresholded product of convective available potential energy (CAPE) and vertical wind shear over a surface-to-6 km layer (S06) constitutes one widely used means of



### Annual Tornado Activity in the U.S. (1955–2013)
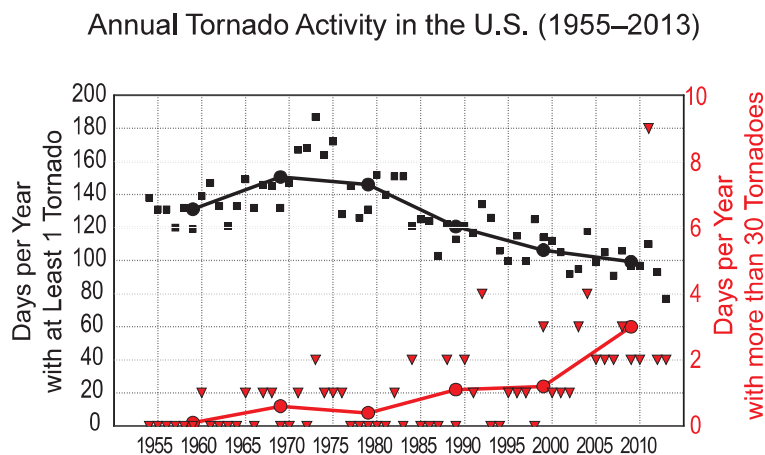
**Figure 9.3:** Annual tornado activity in the United States over the period 1955–2013. The black squares indicate the number of days per year with at least one tornado rated (E)F1 or greater, and the black circles and line show the decadal mean line of such *tornado days*. The red triangles indicate the number of days per year with more than 30 tornadoes rated (E)F1 or greater, and the red circles and line show the decadal mean of these *tornado outbreaks*. (Figure source: redrawn from Brooks et al. 2014[41]).

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